Spray Combustion Cross-Cut Engine Research

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Sandia National Laboratories

FY 2014 DOE Vehicle Technologies Program Annual Merit Review
Project ACE005, 1:45 – 2:15 PM, Tuesday, 17 June 2014

Sponsor: **DOE Vehicle Technologies Program**
Program Managers: **Gurpreet Singh and Leo Breton**

Overview

Timeline

- Project provides fundamental research that supports DOE/ industry advanced engine development projects.
- Project directions and continuation are evaluated annually.

Budget

- Project funded by DOE/VT:
  FY13 - $740K
  FY14 - $800K

Barriers

- Engine efficiency and emissions
- Understanding direct-injection sprays
- CFD model improvement for engine design/optimization

Partners

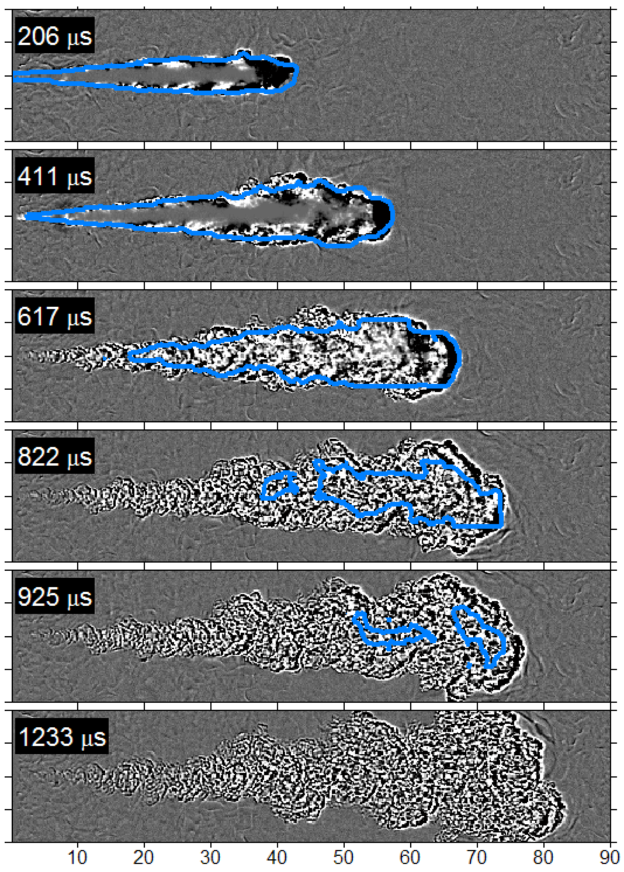
- 15 Industry partners in MOU: Advanced Engine Combustion
- Engine Combustion Network
  - >15 experimental + >20 modeling
  - >120 participants attend ECN3
- Project lead: Sandia
  - Lyle Pickett (PI)

Spray combustion research is relevant for high-efficiency engines.

- Future high-efficiency engines use direct injection.
  - Diesel, gasoline direct injection, partially-premixed compression ignition
- Complex interactions between sprays, mixing, and chemistry.
  - Two-phase system, including multiple injections
  - Spray-induced mixture preparation
  - Complicated internal flows within injectors
- Optimum engine designs discovered only when spray modeling becomes predictive.
  - Predictive modeling shortens development time and lowers development cost.
  - Makes efficient engines more affordable.
- Relevant to EERE Advanced Combustion Engine research and development goals.

Schlieren: vapor boundary

BLUE: liquid boundary

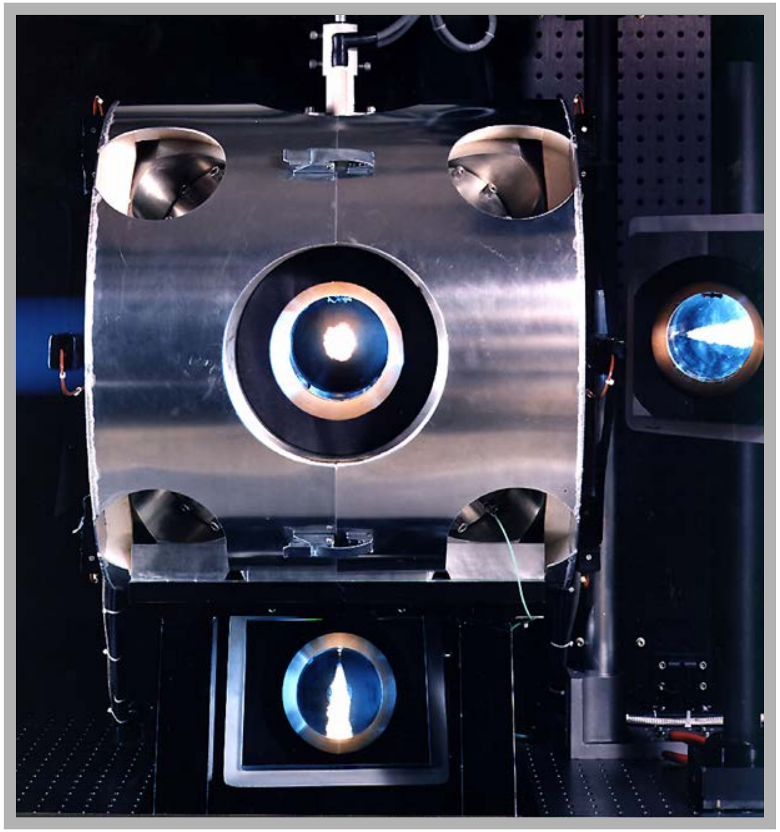


Project Objectives – Relevance

Major objective: experimentation at engine-relevant spray conditions, allowing development of predictive computational tools used by industry.

- Lead an experimental and modeling collaboration through the Engine Combustion Network with >100 participants (http://www.sandia.gov/ECN)
  - Use target conditions specific to low-temperature diesel and DI gasoline.
    - Development of quantitative datasets that provide a pathway from experimental results to more predictive CFD modeling in codes used by industry.
    - Our research spans from internal geometry characterization to combustion.
- Provide fundamental understanding of near-field development to make transient diesel spray mixing predictive.
  - Predictive combustion must be preceded by predictive mixing—still a weak link.
- Quantification of combustion indicators (ignition site, lift-off length, soot).
  - Models are deficient in these areas with serious consequences on emissions and efficiency.
- Understanding plume-plume interaction and “collapse” of gasoline direct-injection sprays.
  - Major impact on wall wetting, PM formation, knock, and so forth.

Experimental approach utilizes well-controlled conditions in constant-volume chamber



- Well-defined ambient conditions:
  - 300 to 1300 K
  - up to 350 bar
  - 0-21% O_2 (EGR)
- Injector
  - single- or multi-hole injectors
  - diesel or gasoline (cross-cut)
- Full optical access
  - 100 mm on a side
- Boundary condition control needed for CFD model development and validation.
  - Better control than an engine.
  - Easier to grid.

How does this experimental data impact computational tools used by industry?

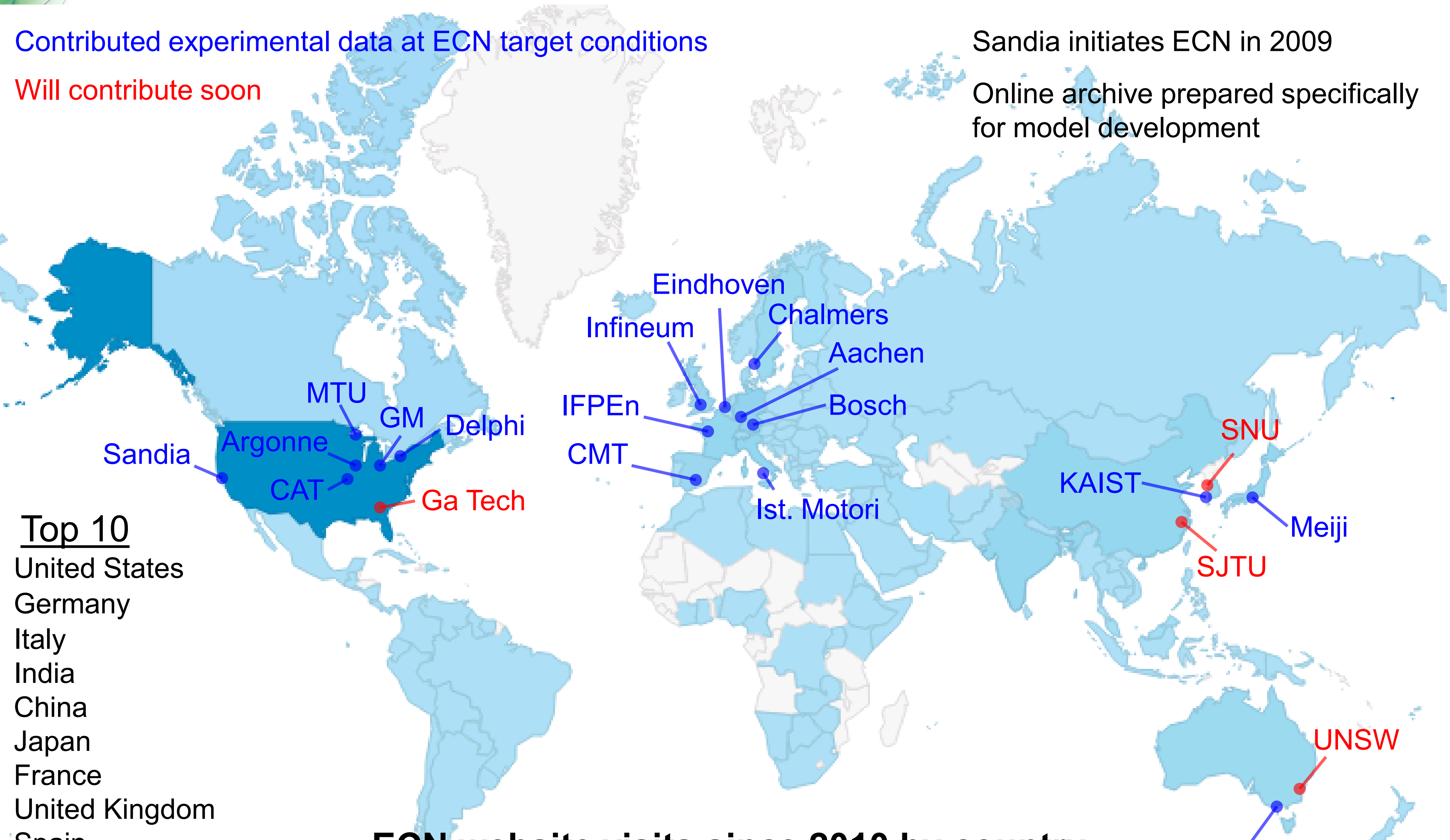
Results are disseminated, and combined from multiple institutions, using the Engine Combustion Network

Contributed experimental data at ECN target conditions

Will contribute soon

Sandia initiates ECN in 2009

Online archive prepared specifically for model development



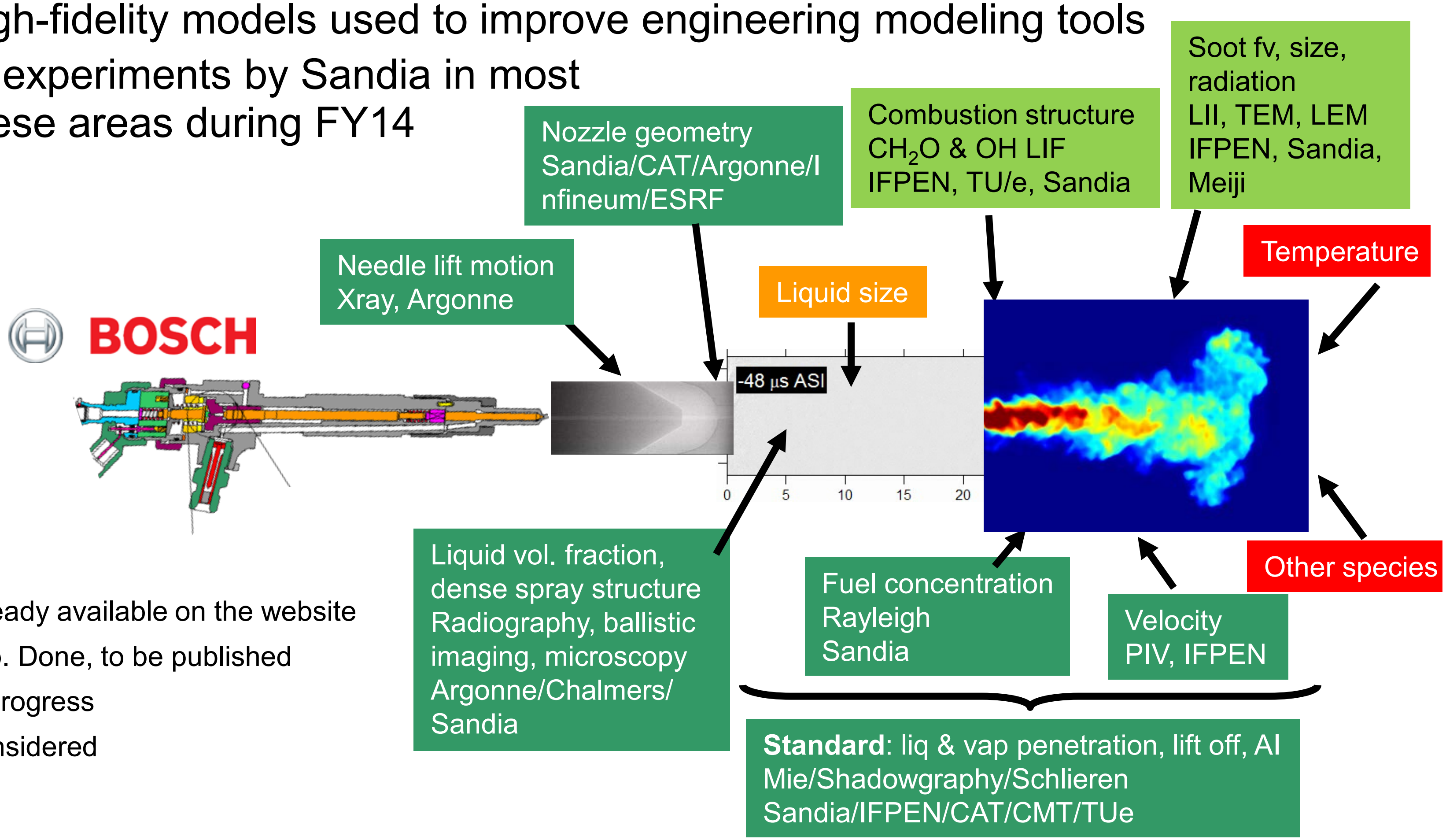
Top 10

United States
Germany
Italy
India
China
Japan
France
United Kingdom
Spain
Australia

ECN website visits since 2010 by country
(www.sandia.gov/ECN)

Leveraging target conditions greatly accelerates research

- Spray A diesel experiment: >40 different measurements by >10 institutions
  - ~15 years of research performed in ~3 years
- Massive, focused effort using advanced modeling at these conditions (>16 teams)
  - High-fidelity models used to improve engineering modeling tools
- New experiments by Sandia in most of these areas during FY14



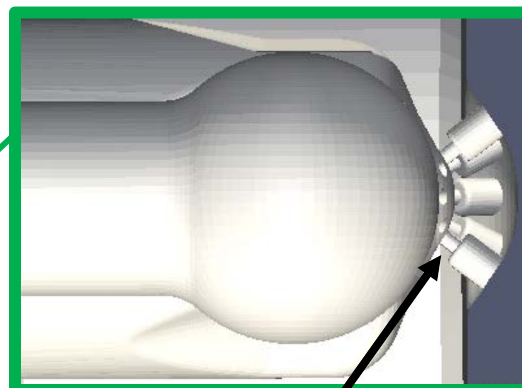
- Already available on the website
- Exp. Done, to be published
- In progress
- Considered

Similar efforts are in place for gasoline direct injection

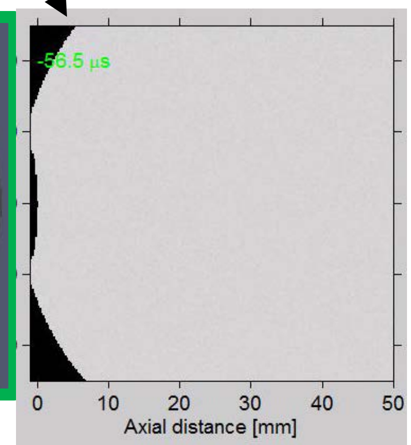
- Spray G gasoline experiment: 10 different measurements by 9 institutions
  - Experimentation just commencing; injectors received in early 2014
  - Modeling (internal flow and external spray) already performed by 4 institutions

Spray G organizer:
Scott Parrish, GM

8-hole, stepped
80° total angle

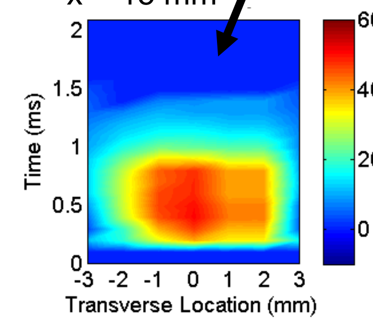


Liq. & vap. penetration
Mie/Schlieren/DBI
Sandia, IFPEN, GM, IM, Melbourne



droplet size,
velocity PDI
GM

axial velocity,
x = 15 mm



Nozzle geometry
x-ray, microscopy
Infineum, ESRF,
Argonne, Sandia

Rate of injection
GM, CMT

Needle movement
Argonne

Liquid mixture fraction
Argonne

Vapor mixture fraction
Sandia

Spray structure
HS microscopy
Sandia

Combustion

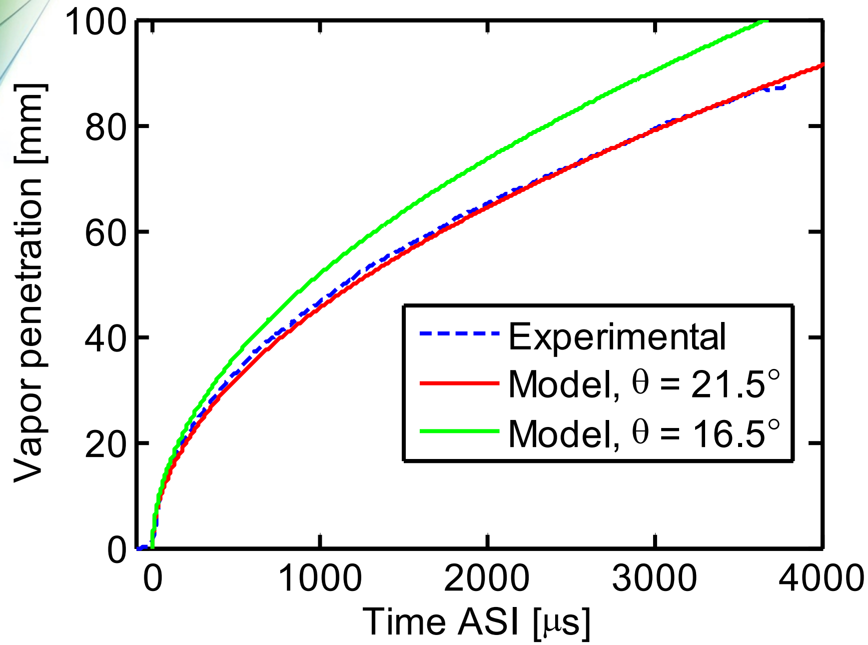
Engine

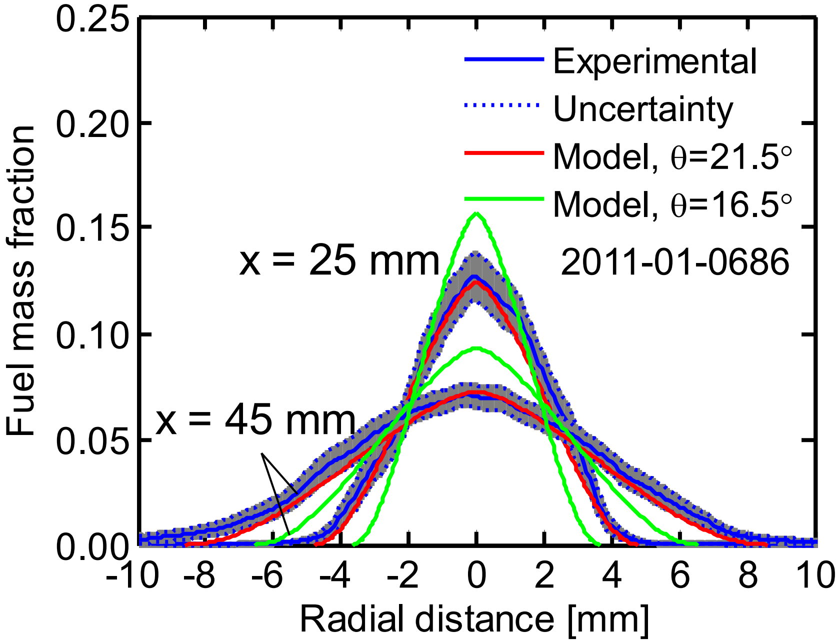
Already on the website
Experiment done
In progress
Considered

Approach - Milestones

- ✓ **June 2013**
  Develop quantitative soot and soot radiation datasets for diesel Spray A and variants
- ✓ **September 2013**
  Use optical microscopy and analysis of x-ray radiography (Argonne) to quantify near-field liquid volume fraction for diesel Spray A
- ✓ **December 2013**
  Quantify the formaldehyde formation on plane with simultaneous high-speed schlieren along a line of sight to reveal the ignition location and timing for diesel Spray A
- ✓ **March 2014**
  Characterize the liquid and vapor penetration, and plume-plume interaction of gasoline Spray G
- ✓ **April 2014**
  Organize ECN3, the third workshop of the Engine Combustion Network, with over 150 web and in-person attendees focused on experimental and modeling advancement
- **May 2014**
  Compare spray and combustion behavior of Spray B (multi-hole) to Spray A
- **July 2014**
  Perform in-situ sampling of vessel gases to understand the role of minor species on ignition and soot formation processes
- **September 2014**
  Investigate the structure of fuel sprays at possible supercritical conditions

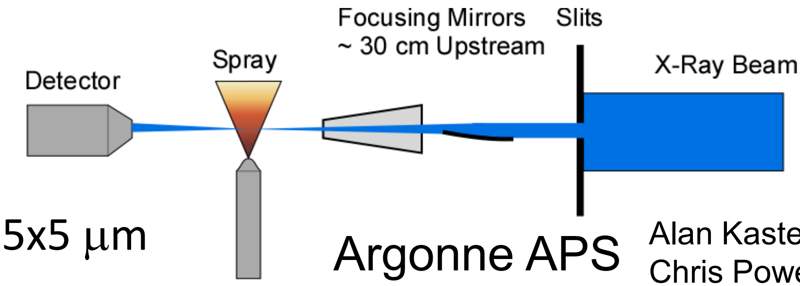
Plume spreading angle is a key parameter for spray mixing, but it is difficult to predict.



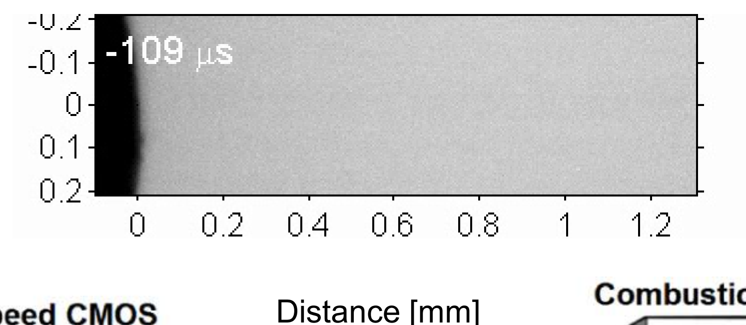


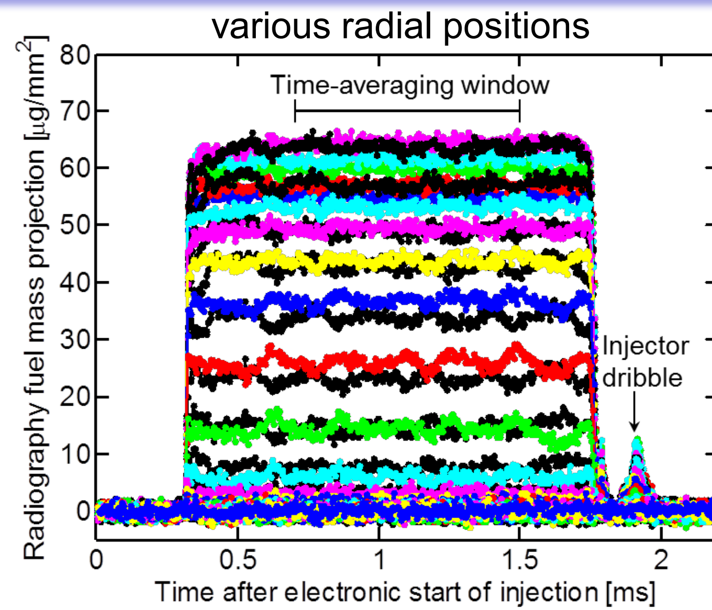
- With proper "spreading angle", fuel jet penetration and mixing are consistent and correct.
- Bottom line: In current CFD codes, the effective spreading angle is not predictable and usually requires substantial tuning of model constants.
- Key objectives:
  - How can this dispersion be made more predictive?
  - What are the underlying physics?

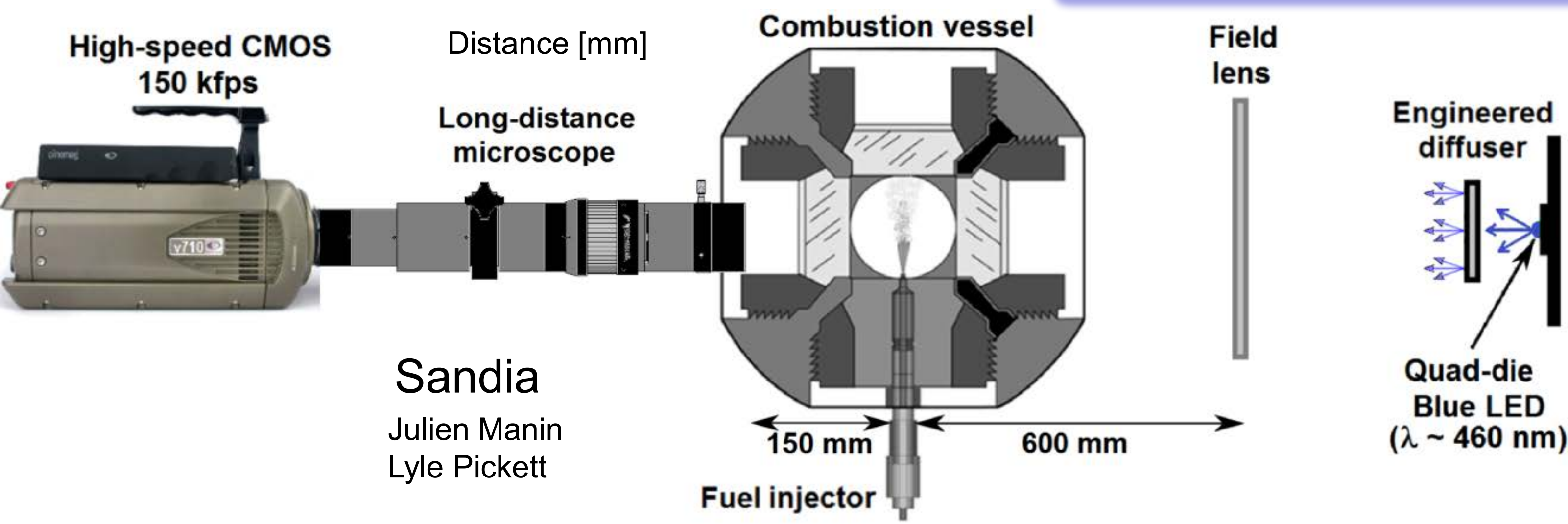
Study near-field of Spray A using optical microscopy (Sandia) and radiography (Argonne)



Alan Kastengren
Chris Powell





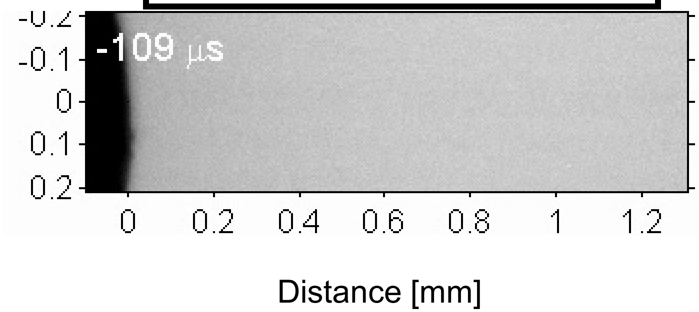


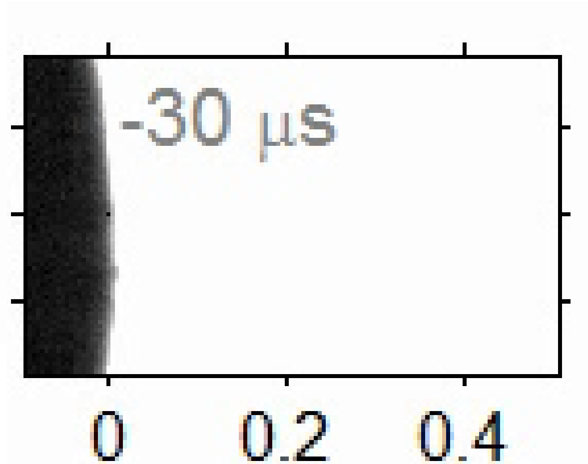
Sandia
Julien Manin
Lyle Pickett

<50 ns pulse

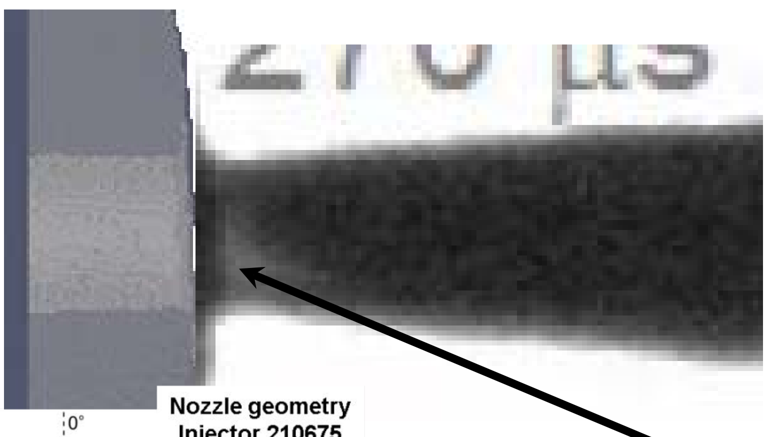
Optical microscopy indicates liquid core at nozzle exit

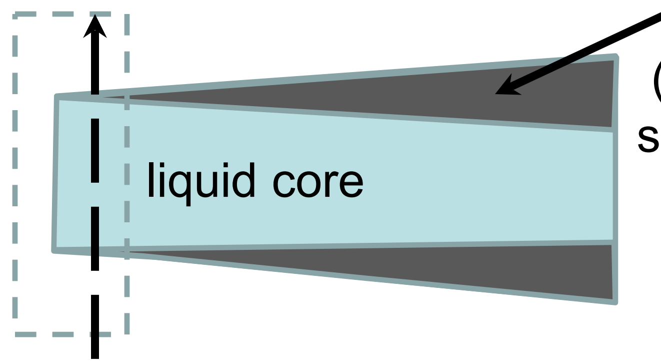
29 bar, 440 K (22.8 kg/m^3)
n-dodecane, 150 MPa, 90^{o}C



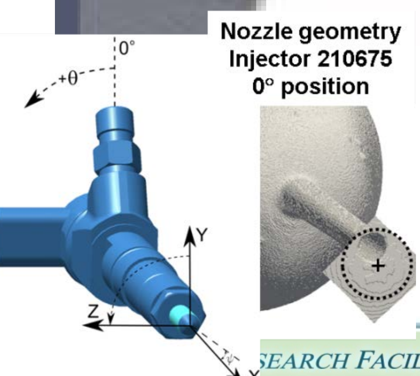


25% display range (white above $I/I_0 = 0.25$)





mixing layer (of curved liquid surfaces/droplets)



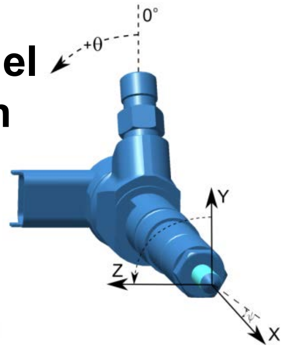
Nozzle geometry
Injector 210675
0° position

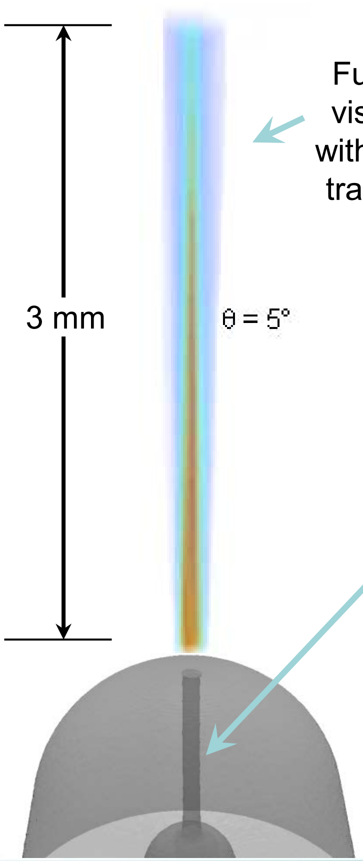
- Higher optical transmission if mixing layer breaks on both sides of spray and there is a pure liquid core

We converted Argonne radiography measurements to local liquid volume fraction using tomography.

Measured fuel distribution

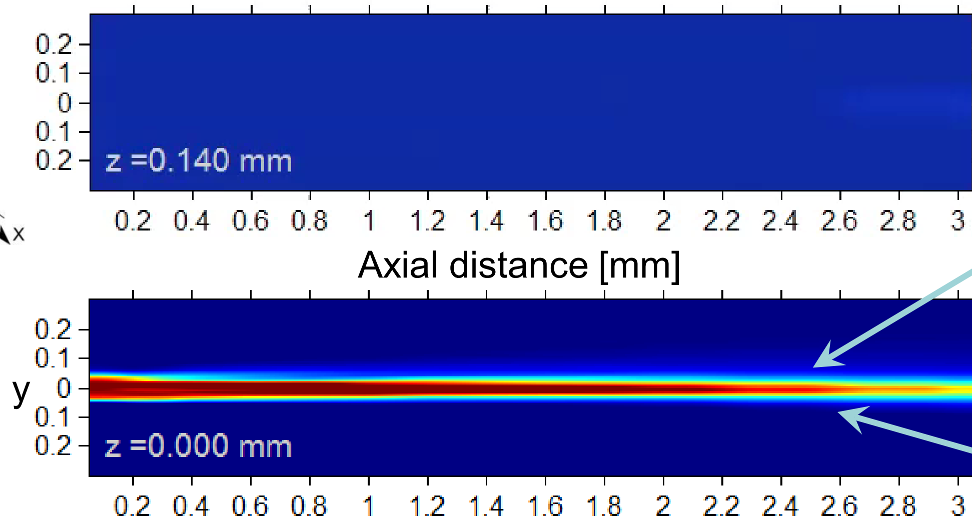
Azimuthal perspective variation





Fuel density visualization with "ramp-up" transparency

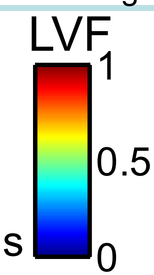
"Fly through" of slices in z direction



Mean of the steady-state period of injection

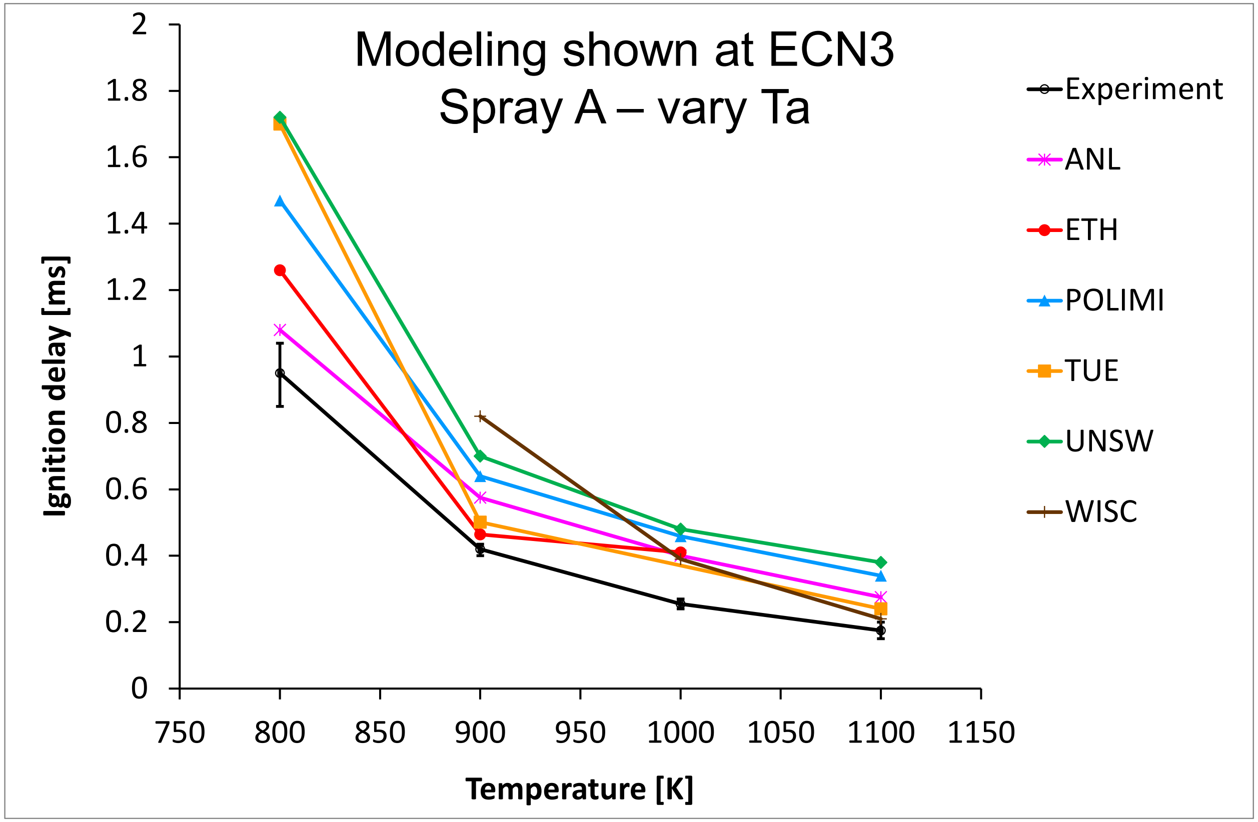
Layer growth stronger on top of spray (linked to hole geometry)

Intact liquid core broken up by 2.5 mm (ensemble- average)



- 3D fuel distribution shows pure liquid to about 2.5 mm
  - High liquid density "hot spots" identified with consistency along axis
  - Elliptical spray shape originating from nozzle geometry persists
- Extremely valuable for serious spray model evaluation
  - Consistency for spray boundary based on optical microscopy with radiography at low projected mass (~0.7 μg/mm^2)
  - see Sandia/Argonne paper SAE 2014-01-1412

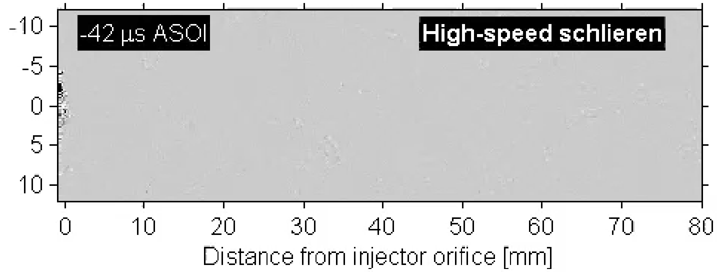
Predicting ignition delay is still one of the most critical issues for predictive spray combustion



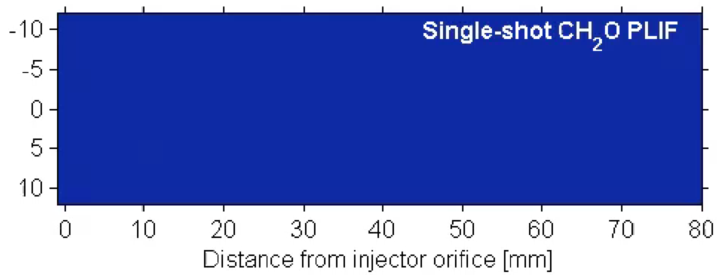
- Identifying low- and high-temperature ignition location, and the transition to steady lift-off length is needed to capture HRR, UHC, soot, pilot ignition.
- Past experimental data lacks time resolution (single shot) or spatial resolution (line of sight) to evaluate critically against models.

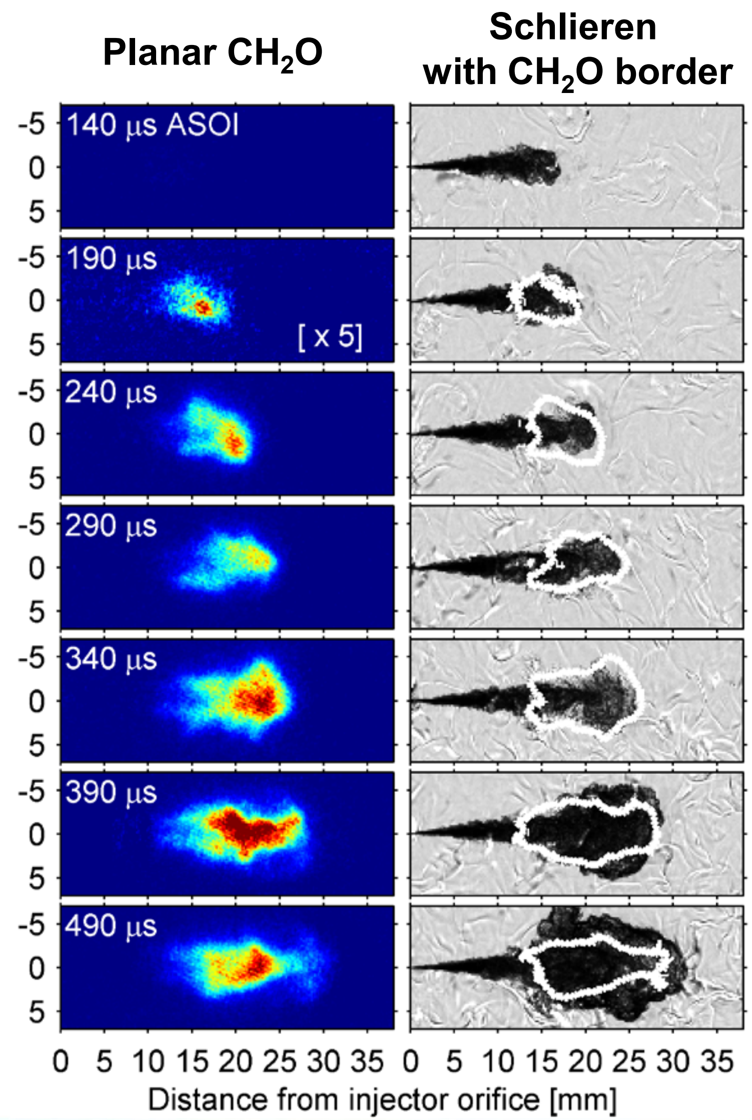
Combine high-speed schlieren with planar formaldehyde LIF to characterize diesel ignition, temporally and spatially

Schlieren (150 kHz) line-of-sight



355-nm LIF (single-shot) planar

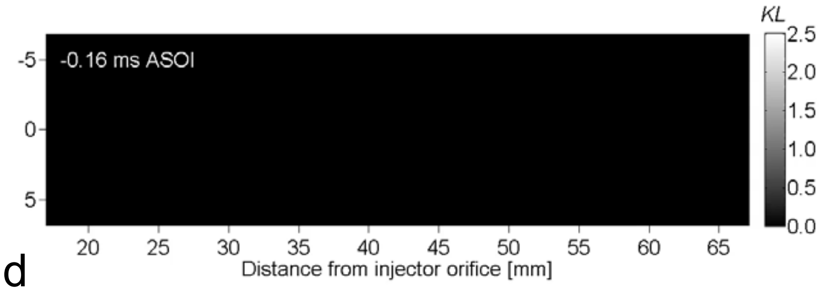




- Refractive index gradients in schlieren soften when formaldehyde forms.
- Formaldehyde LIF occurs slightly before schlieren "softening" (expected difference between planar and line-of sight diagnostics).
- Formaldehyde disappears where high-T ignition occurs (sharp T gradient in schlieren).
- Fast (150 kHz) ign. diag. capabilities clarified.

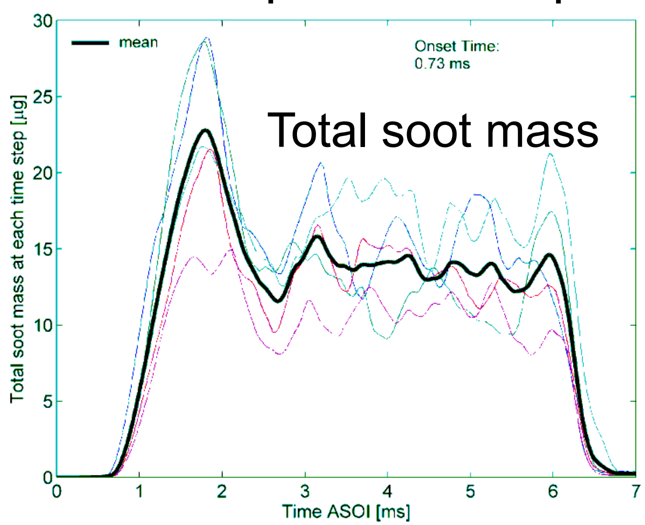
Soot level quantified with time resolution in reacting sprays using extinction imaging

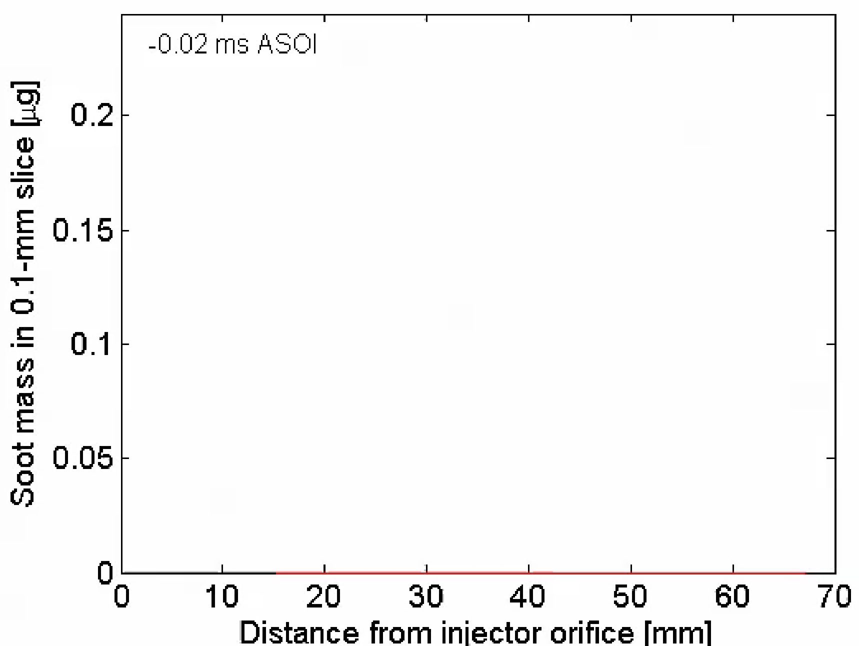
- Provided useful targets for soot modeling efforts including:
  - Soot onset time and location
  - Soot mass or soot volume fraction
  - Transient progression of the 2D soot field with high temporal resolution
- Applied to Spray A variants
  - Ambient temperature, density, EGR
  - Available on ECN website. 3 CFD teams have modeled.
- Soot radiation profiles completed



$$\rho KL \frac{\lambda}{k_e} = \rho \int f_v \, dl \;\; [g/cm^2]$$

$$\text{mass}_{soot} = \sum \rho KL \frac{\lambda}{k_e} \times \text{ pixel area}$$

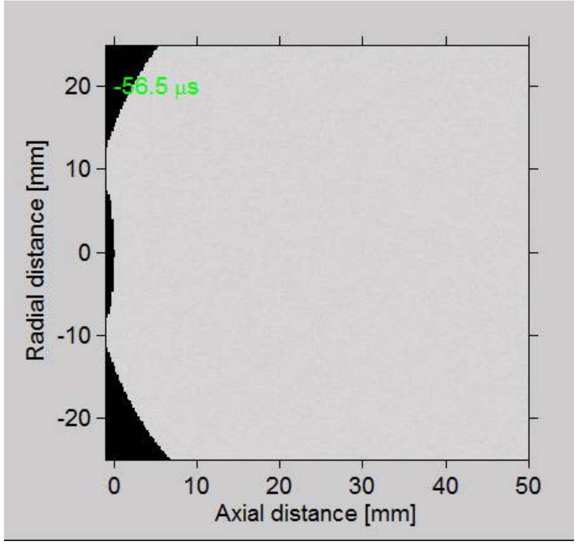




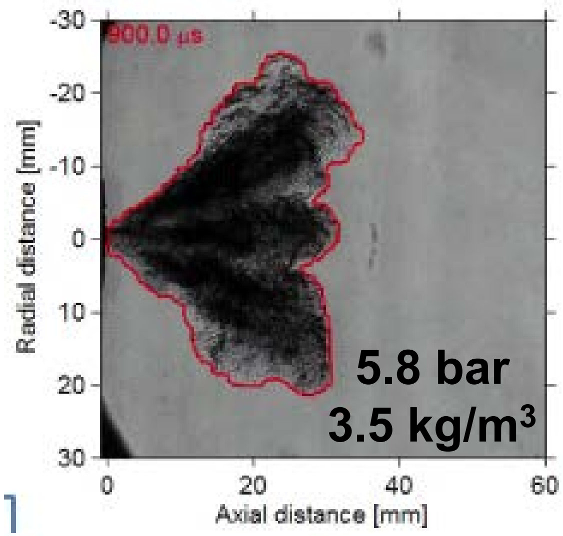
Gasoline direct-injection Spray G shows strong dependencies upon ambient conditions

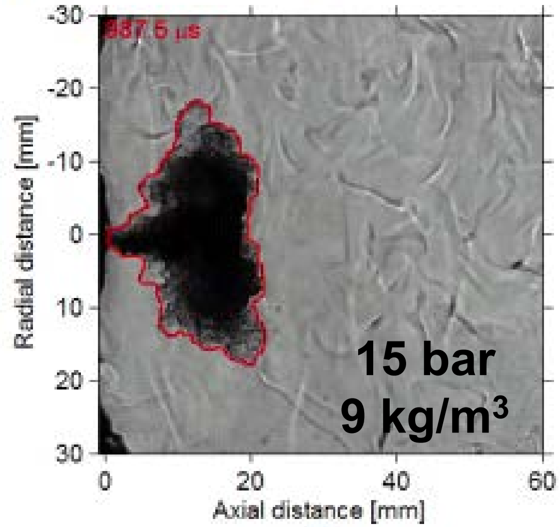
- Multiple diagnostics performed at Spray G target condition
  - simultaneous front view, side view, + microscopy
  - combined with other ECN institutions
- Parameter sweeps also performed
- Spray collapse occurs at higher ambient density
  - Collapsed core actually results in higher axial penetration (after injection) than lower density cases where plumes remain separate.

diffused backlighting (liquid)



schlieren





Spray G target conditions

Parameter	Value
Fuel	Iso-octane
Fuel pressure	200 bar
Fuel temperature	90° C
Injector temperature	90° C
Ambient temperature	300° C
Ambient density	3.5 kg/m^3
– 5.97 Bar (Nitrogen)	
Injected quantity	10 mg
Number of injections	1

Responses to previous year reviewer comments

- At last merit review, we spent more time with gasoline sprays. Reaction:
  - "gasoline spray measurements should be accelerated"
  - "greater balance between diesel and gasoline work should be encouraged"
  - Response: we will seek to strike a balance that includes both. Strong potential for new work with gasoline given that Spray G only recently arrived.
- Spray chamber versus an engine:
  - "high-temperature/high-pressure chambers provide good optical access and mimic certain static conditions in the engine,…but do have some limitations"
  - "ask the modelers to extend their predictions to an environment in which the pressure (and temperature) was (were) changing, as it did during engine expansion"
  - Response: Through our strong ECN collaboration, our chamber-characterized Spray B (diesel) and Spray G (gasoline) will both be used in engines this next year. Critical questions about the engine environment (expansion and flows) will be addressed. Remember that our work is only funded for experiments, but we have organized the ECN to provide the tightest possible connection to modeling.

Close collaboration and pathway to better CFD tools

Experiment
Sandia
Argonne
IFPEN
CMT
CAT
GM
Delphi
Bosch
TU/e
Ist. Motori
Mich. Tech.
Meiji
Infineum
Chalmers
KAIST
Aachen
Melbourne

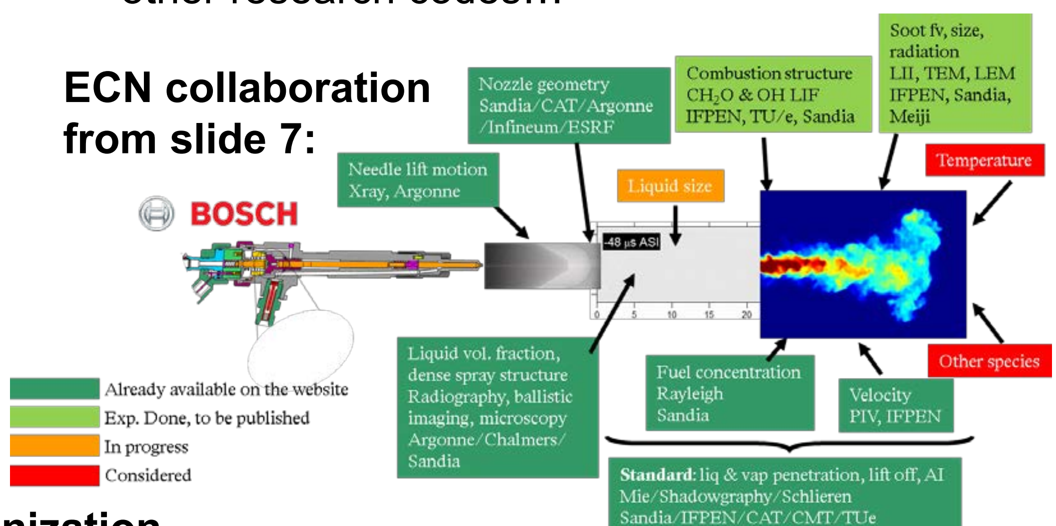
CFD codes used
CONVERGE
Star CD
Open FOAM
KIVA
ANSYS Fluent & CFX
FORTE
RAPTOR
other research codes…

CFD approaches
RANS
LES
High-fidelity LES
Eulerian-Eulerian
Eulerian-Lagrangian
Dense fluid
many spray and combustion variants…

Modeling submissions
Sandia
Argonne
IFPEN
CMT
PoliMi
UMass
UNSW
Penn St.
TU/e
UW-Madison
Purdue
ETH-Zurich
Aalto
Aachen
DTU
Cambridge
Georgia Tech
Chalmers
GM…

Most industry use ECN data to test their CFD practices

ECN collaboration from slide 7:



ECN organization

- Monthly web meetings
- Workshop organizers gather experimental and modeling data, perform analysis, understand differences, provide expert review
- Very tight coordination because of target conditions

Future work

- Expand Spray G gasoline dataset (FY15)
  - Interaction of inner and outer hole using microscopy.
  - Conditions that span from flash boiling to late injection.
  - Quantitative mixture fraction for better model validation.
  - Fuel effects (ethanol) / multiple short injections.
- Diesel research activities (FY14 – FY15)
  - Multi-hole Spray B already shows significant differences in near-field structure and transients. How does this affect ignition/combustion/soot?
  - Investigate large-nozzle injectors (0.2 mm diameter) to intentionally create interaction between liquid regions and combustion regions of the spray.
  - Perform in-situ sampling of vessel gases to understand the role of minor species on ignition and soot formation processes.
  - Investigate the structure of fuel sprays at possible supercritical conditions, spanning a range of ambient conditions and fuels (light and heavy).
  - High-speed planar ignition detection using burst laser.

Presentation Summary

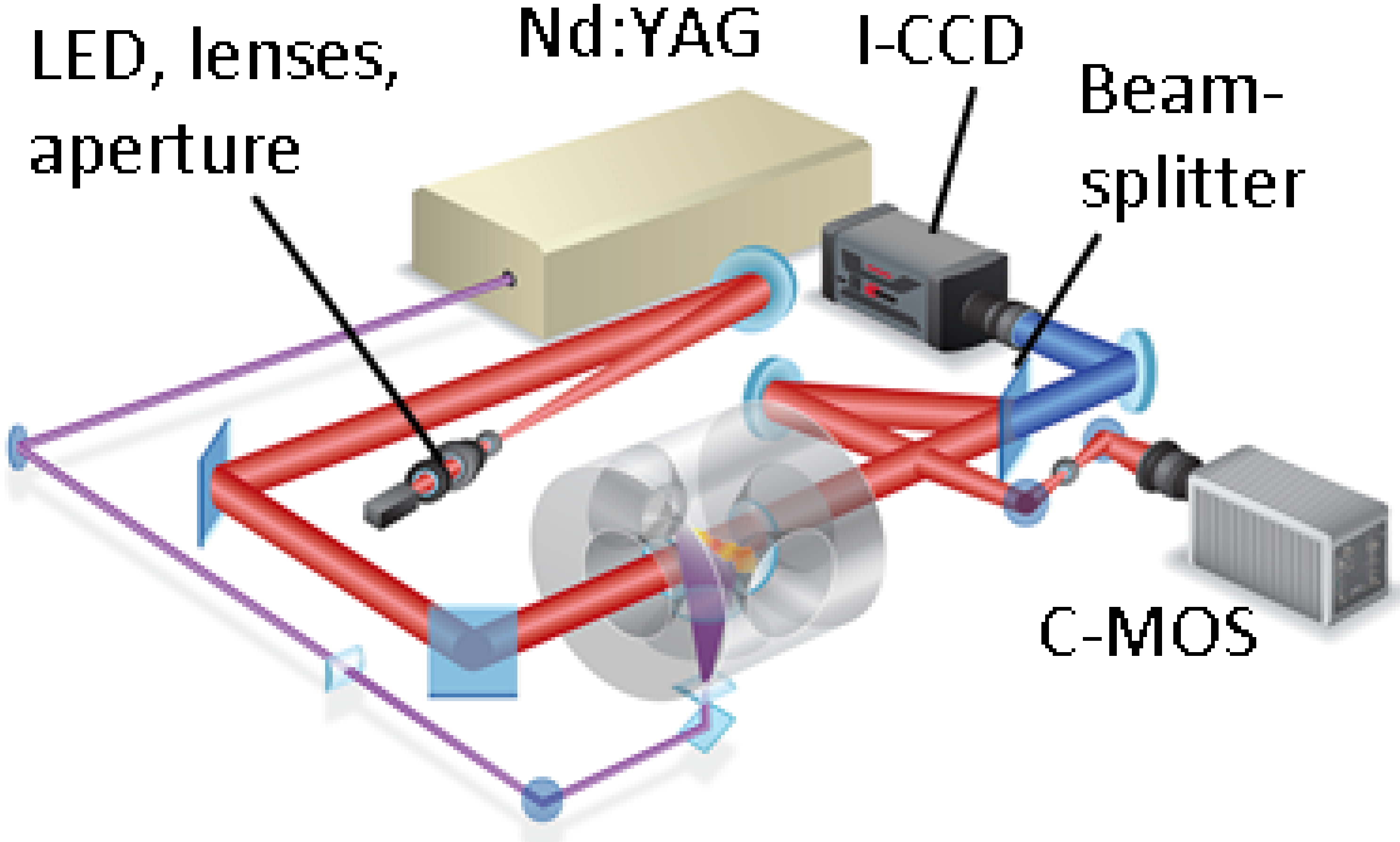
- Project is relevant to the development of high-efficiency, low-emission engines, which all use direct-injection sprays.
  - Observations of combustion in controlled environment lead to improved understanding/models for engine development.
  - Sprays of interest will also be characterized in engines.
- FY14 approach addresses deficiencies in spray combustion modeling.
  - Joining of optical microscopy and x-ray radiography provides insights into the near-field spray development—a weak link for predictive spray modeling.
  - Understanding of ignition events expanded through simultaneous planar (formaldehyde LIF) and line-of-sight (150 kHz schlieren) measurements.
  - Quantitative soot and soot radiation datasets are now available to address the transient of soot formation and oxidation.
  - Gasoline direct-injection sprays shows strong dependencies upon ambient conditions, confirmed by a combination of diagnostics.
- Collaboration through the ECN expanded to accelerate research and provide a pathway for improved CFD tools used by industry.
- Future plans will continue ECN-type research in diesel and gasoline.

Acknowledging FY14 staff and visitors performing spray combustion research at Sandia

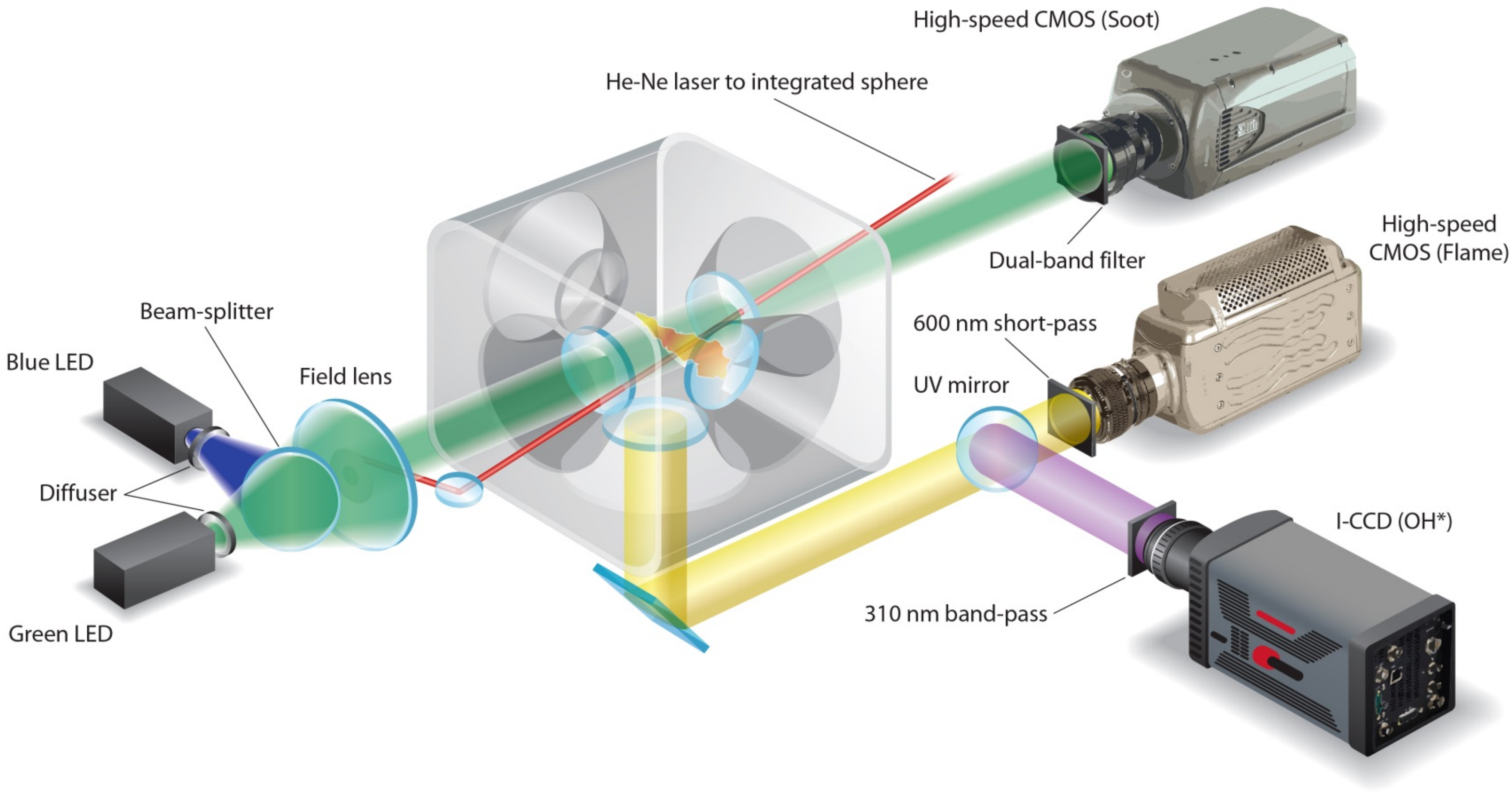
- Scott Skeen, Sandia National Laboratories
- Julien Manin, Sandia National Laboratories
- Yongjin Jung, Korean Adv. Inst. of Science and Technology (KAIST)
- Guillaume Lequien, Lund University

Technical Backup Slides

Optical arrangement for simultaneous high-speed schlieren imaging and formaldehyde PLIF

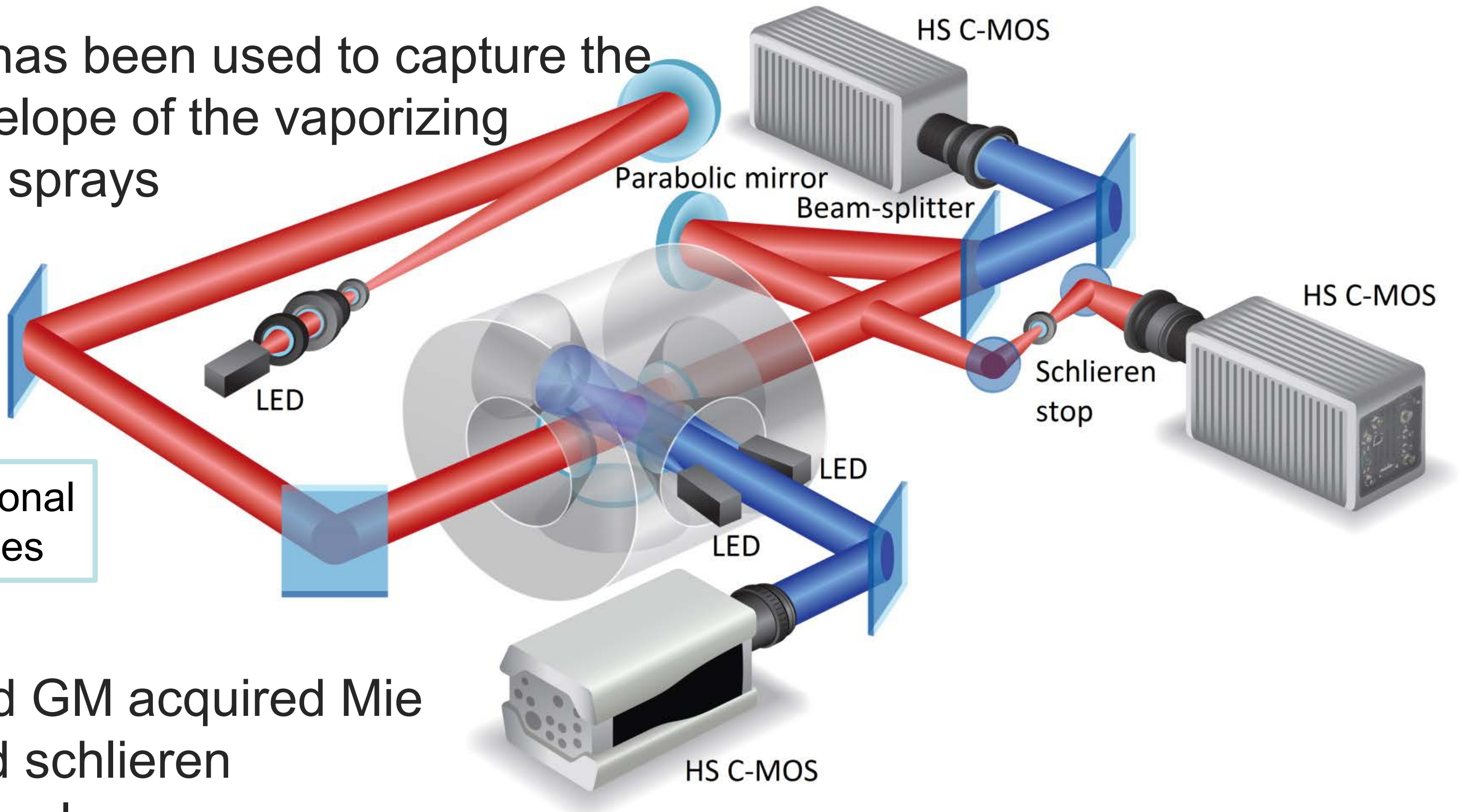


Diffused Back Illumination for quantification of soot



Optical setup for gasoline direct injection visualization

- Mie scatter has been used by Sandia, GM and Istituto Motori to measure liquid penetration
- Schlieren has been used to capture the global envelope of the vaporizing iso-octane sprays



Sandia National Laboratories

- Sandia and GM acquired Mie scatter and schlieren simultaneously
- Note that GM used an image straddling strategy (1 frame Mie, 1 schlieren)
- Sandia also performed front-view Mie scatter visualization of the sprays

Spray G injector

Parameter	Consensus
• Number of holes	8
• Spray shape	circular
• Spray angle	80°
• Bend angle	0 °
• L/D ratio	1.4
• Hole shape	straight
• Manufacturing	EDM
• Flow rate	15 cc/s @ 10 MPa